Unit source area data: Can it make a difference in calibrating the hydrologic response for watershed-scale modeling?

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Abstract: Watershed computer models such as the Soil and Water Assessment Tool (SWAT) contain parameters that describe watershed properties such as vegetative cover, soil characteristics, or landscape features. For investigations that involve changes in land cover or land management on agricultural lands, proper adjustment of these parameters is important not only for runoff estimation, but also for the simulation of sediment, nutrients, and other pollutants. However, these parameters may only be known for a few small, homogeneous areas, and the usefulness of such parameters in calibrating the runoff response for a watershed scale model such as SWAT is not well documented. The objective of this study was to determine if model parameters that govern the surface runoff response in SWAT that were calibrated from rain-fed unit source area watersheds could be scaled up to provide accurate runoff simulations at a watershed scale. Model testing was conducted on four unit source area watersheds that consisted of homogeneous Bermuda grass, pasture, and winter wheat land cover types and three larger subwatersheds of the Little Washita River Experimental Watershed in southwestern Oklahoma. Data from the unit source area watersheds were used to calibrate parameters in SWAT that govern only the surface runoff output from the model. These parameter values were extended to the larger, 160 km^2 (61.9 mi^2) subwatershed 526, and model simulations were then evaluated by examining both the surface runoff and total water yield response of the model. Simulation results from the unit source area watersheds suggest that the soil evaporation compensation factor (ESCO) in SWAT not only reflects soil field conditions for which it was intended to describe, but the impact of land management conditions on surface runoff response as well. Findings from this research indicate that if a value of ESCO that was calibrated from the unit source area watershed data for winter wheat was applied at the watershed scale, it would lead to model simulations that give a surface runoff to total runoff fraction that is more than 15% too high. Due to uncertainties in relating ESCO to soil and land management properties, results of this study suggest that runoff data from unit source area watersheds may be best suited for calibrating infiltration functions or verifying values of the runoff curve number for watershed simulations.

Key words: calibration—hydrology—modeling—simulation—SWAT

Pollution of streams, channels, and lakes by runoff from agricultural fields has been a major concern in the United States for a number of decades. Pollutants such as sediment and phosphorous that enter waterways adversely affect downstream water supplies, aquatic and wildlife habitat, and recreational opportunities. Conservation practices that are placed on croplands to protect fields from excessive runoff and soil losses provide one means of protecting the environment from the harmful effects of pollutants. Hydrologic simulation models that track the movement of runoff and pollutants from agricultural fields to downstream locations within

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a watershed represent valuable tools that can be used to evaluate the benefits of various conservation practices on reducing pollutant levels.

Recent advances in computing capability and geographical information systems (GIS) have led to increasingly sophisticated watershed models that incorporate topography, soils, climate, land use, and land management characteristics and address a range of issues related to low flow management, water availability, flood control, and water quality in various agricultural settings. Examples of event based and continuous watershed simulation models that have been used throughout the United States during the past few decades include the Dynamic Watershed Simulation Model (DWSM; Borah and Bera 2003), Kinematic Runoff and Erosion Model (KINEROS; Smith et al., 1995), Areal Non-point Source Watershed Environmental Response Simulation model (ANSWERS; Beasley et al., 1980), Agricultural Non Point Source Pollution Modeling System Continuous Version (AnnAGNPS; Bingner and Theurer, 2001) and Soil and Water Assessment Tool (SWAT; Arnold et al. 1998). These models are capable of simulating complex hydrologic processes on agricultural watersheds and are useful as analytical tools for estimating the effects of conservation practices at various spatial and temporal scales. They can also be used to evaluate total maximum daily load (TMDL) standards and to select suitable land use and conservation practice scenarios that help reduce damaging effects of storm water runoff on water bodies and the landscape (Borah and Bera 2003).

Because hydrologic simulation models are based on knowledge available regarding the movement of water in the physical environment, they are incomplete in their description of both the elements and processes present in that environment. To best represent hydrologic processes that exist on a particular watershed, computer simulation models must be calibrated. Calibration is the process by which model parameters are adjusted in such a way so that measured and simulated hydrologic responses match as closely as possible. To ensure that a simulation model provides reliable simulations of runoff, sediment, nutrients, and other water quality variables, observed data are necessary for model calibration (Van Liew and Garbrecht 2003).

Data collected from studies on test plots or unit source area (a drainage area with homogeneous soil, topographic and land cover features) watersheds during the past several decades provide a rich source of information for quantifying the impact of specific climatic, soils, topographic, and land use conditions on hydrologic response. The wealth of data available from these long term studies has been used to develop tools for runoff and soil loss prediction such as the runoff curve number (CN2) and the universal soil loss equation. The use of these data in watershed scale models holds promise for quantifying the cause and effect relationships between climatic, landscape, and anthropogenic factors and hydrologic response at the watersheds scale (Water Quality and Watershed Research Laboratory 1983; Harmel et al. 2000). However, it is important to recognize that scaling up from point measurements for watershed scale applications substantially increases the uncertainty associated with output from model simulations and the evaluation of modeling assessments (Cerdan et al. 2004; Western and Bloschl 1999). Extrapolating results from one scale to another may have serious consequences, especially when heterogeneity predominates (Quattrochi and Goodchild 1997). As field plot and unit source area watershed (USAW) data continue to be collected and analyzed across the United States, a need exists to develop ways in which these data can be coupled with water quantity and quality data collected at the watershed scale so that reliable assessments of the impact of conservation practices on downstream runoff, sediment, nutrients and other water quality constituents can be developed.

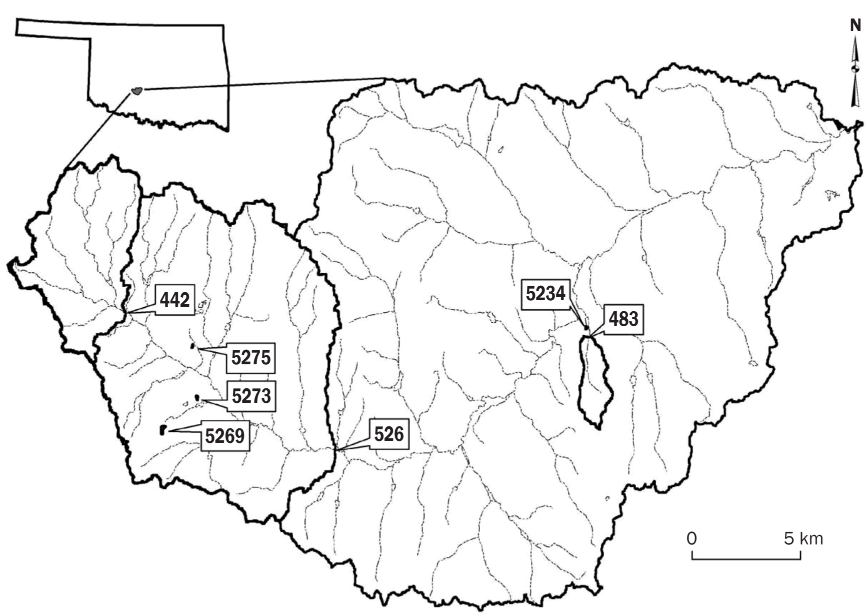
Previous experience using SWAT has demonstrated that model parameters including the CN2, the available soil water content, and the soil evaporation compensation factor (ESCO) that governs surface runoff response are among the most sensitive parameters in the model for simulations performed on rain-fed watersheds (Feyereisen et al. 2005; White and Chaubey 2005). Proper adjustment of these parameters is therefore critical not only for runoff estimation but also for the simulation of sediment, nutrients, and other water quality constituents for projects that include the implementation of changes in land cover or land management on agricultural lands. Although the CN2 and available soil water content are concepts that are widely known among hydrologic practitioners today, the impact of the ESCO on hydrologic response in SWAT is not well documented nor understood. A need therefore exists to better understand the interactions of these parameters on runoff response so that model simulations that are performed at a watershed scale can be used to reliably predict the impact of land use and management practices on hydrologic response.

Bearing in mind the inherent problems of utilizing data collected at one scale for application to another, we performed a study to determine the feasibility of using unit source area data at the watershed scale. Our objective was to determine whether or not model parameters that govern the surface runoff response in SWAT that were calibrated from rain-fed homogeneous, USAWs could be scaled up to provide accurate runoff simulations at a watershed scale that consisted of heterogeneous land cover, soils, and topographic features. Data from four USAWs that ranged in size from 0.6 to 4 ha (1.5 to 9.9 ac) within the Little Washita River Experimental Watershed (LWREW) in southwestern Oklahoma were used to calibrate parameters in SWAT that govern the surface runoff response of the model. Model simulations were also performed on a 4.3 km^2 (1.7 mi^2) subwatershed and a 33.3 km^2 (12.9 mi^2) subwatershed to substantiate parameter values determined from calibrating the USAWs. SWAT was then used to simulate the runoff response from a 160 km^2 (61.9 mi^2) subwatershed within the LWREW. The strengths and weaknesses associated with extending values of these calibrated parameters to the larger subwatershed were then evaluated by examining both the surface runoff and water yield (total runoff) output from the model.

Materials and Methods

Test Watersheds. Seven subwatersheds within the LWREW were selected for this investigation (figure 1). The climate in the region is subhumid to semiarid, with an average annual precipitation of about 795 mm (31.3 in), based on data collected by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) from 1961 to 2000. Topography of the LWREW is characterized by gently to moderately rolling hills, and the soil types primarily consist of silt loams (29%), loams (17%), fine sandy loams (41%), and sandy

Figure 1
Location of the test watersheds in the Little Washita River Experimental Watershed.



loams (13%) (USDA Natural Resources Conservation Service 1992). Land use types include rangeland and pasture (66%), cropland (19%), forest (9%) and miscellaneous (6%—urban, abandoned oil fields, farmsteads, ponds) (Allen and Naney 1991). From 1980 to 1985, a model implementation project was conducted on the LWREW to study the effects of intensive land treatment on the quality of water in the basin (Allen and Naney 1991). Eleven USAWs, ranging in size from 0.5 to 5.7 ha (1.2 to 14.1 ac), were instrumented within the LWREW to monitor smaller streams that flow into the main channel. These USAWs consisted of homogeneous pasture and winter wheat cover types. Four of these USAWs referred to as 5273 (improved Bermuda grass), 5234 (poor native grass pasture), 5275 (conventional tilled winter wheat), and 5269 (conventional tilled winter wheat) (figure 1) were employed in this investigation. A typical management operation schedule on the winter wheat USAWs consisted of harvest during late May or early June, multiple tillage operations to incorporate remaining crop residue into the upper several centimeters of the soil surface during July, fertilization and seed bed preparation during latter September, and planting during late September or early October. Hydrologic conditions were also monitored on three subwatersheds within the LWREW referred to as 483, 442, and 526, all three of which consisted of mixed land uses. Precipitation on the LWREW was measured by a network of rain gages spaced on a 5 km by 5 km (3 mi by 3 mi) grid, and runoff observations were made by H flumes at the outlet of the USAWs and stream gages at the outlet of the larger subwatersheds. Listing of the drainage areas, percent land use types, and percent soil types for each of the respective USAWs and subwatersheds is presented in table 1.

Model Description. SWAT is a river basin, or watershed, scale model developed by ARS to simulate the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and land management conditions over long periods of time (Neitsch et al. 2002; Arnold et al. 1998). The model incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins) (Williams et al. 1985). Specific models that contributed to the development of SWAT include CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al. 1987), and EPIC (Erosion-Productivity Impact Calculator) (Williams et al. 1984). The USDA Soil Conservation Service (SCS) CN2 is used to estimate surface runoff from daily precipitation (USDA SCS 1986). The curve number is adjusted according to soil moisture conditions in the watershed (Arnold et al. 1993). SWAT can also be run on a sub-daily time step basis using the Green and Ampt (Green and Ampt 1911) infiltration method. Other hydrologic processes simulated by the model

Table 1
Number of subbasins, number of hydrologic response units, drainage areas, land use types, and soil types for the Little Washita River experimental subwatersheds.

				Land use type				Soil type			
Watershed	No. of subbasins	No. of HRUs	Drainage area (km^2)	Range/ pasture	Crop	Forest	Misc.	Silt loam	Loam	Fine sandy loam	Sandy loam
5273	1	1	0.0147	100%	0%	0%	0%	100%	0%	0%	0%
5234	1	1	0.0116	100%	0%	0%	0%	0%	100%	0%	0%
5275	1	1	0.006	0%	100%	0%	0%	100%	0%	0%	0%
5269	2	3	0.0417	0%	100%	0%	0%	100%	0%	0%	0%
483	1	4	4.3	79%	12%	6%	3%	0%	22%	78%	0%
442	5	20	33.3	49%	45%	1%	5%	100%	0%	0%	0%
526	70	353	160	61%	28%	8%	3%	78%	0%	15%	7%

Note: HRU = hydrologic response unit.

include evapotranspiration, infiltration, percolation losses, channel transmission losses, channel routing, and surface, lateral, shallow aquifer, and deep aquifer flow (Arnold and Allen 1996). The CN2 option (Neitsch et al. 2002) was adopted in this study because the selection of curve number values from field observations was a more straightforward approach than the estimation of infiltration parameters for the Green and Ampt infiltration method. Use of the curve number method in turn facilitated the comparison of simulated runoff responses among the USAWs and subwatersheds, given the various land cover and soil features represented within the study area.

Calibration Parameters. Based on recommendations by Neitsch et al. (2002) for rain-fed watersheds, eleven calibration parameters that govern rainfall/runoff processes in SWAT were selected for model calibration of the hydrologic response of subwatersheds 483, 442, and 526. Model parameters were grouped into three categories, as shown in table 2: those which were considered to predominantly govern surface, those that govern subsurface and those that govern basin response.

Table 2
A listing of parameters, their descriptions, and units that were calibrated in SWAT.

Parameter	Description	Units
	Parameters governing surface water response	
CN2	SCS runoff curve number	None
ESCO	Soil evaporation compensation factor	None
SOL_AWC	Available soil water capacity	mm mm^{-1}
	Parameters governing subsurface water response	
GW_REVAP	Groundwater “revap” coefficient	None
REVAPMN	Threshold depth of water in the shallow aquifer for “revap to occur”	mm
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	mm
GW_DELAY	Groundwater delay	Days
ALPHA_BF	Baseflow alpha factor, or recession constant	Days
RCHRG_DP	Deep aquifer percolation fraction	Fraction
	Parameters governing basin response	
SURLAG	Surface runoff lag time	Days
CH_K2	Channel hydraulic conductivity	mm hr^{-1}

Calibration parameters governing the surface water response in SWAT include the CN2, the ESCO, and the available soil water capacity (SOL_AWC). The CN2 is used to compute runoff depth from total rainfall depth. It is a function of watershed properties that include soil type, land use and treatment, ground surface condition, and antecedent soil moisture condition. The ESCO adjusts the depth distribution for evaporation from the soil to account for the effect of capillary action, crusting, and cracks. The SOL_AWC is the volume of water that is available to plants if the soil moisture level was at field capacity. It is estimated by determining the amount of water released between in situ field capacity and the permanent wilting point. Parameter values of SOL_AWC that are calibrated in SWAT are expressed as percent change from initial values in the model.

Six calibration parameters govern the subsurface water response in SWAT. One of these parameters is referred to as the ground water “revap” coefficient (GW_REVAP), which controls the amount of water that will move from the shallow aquifer to the root zone as a result of soil moisture depletion and the amount of direct ground water uptake from deep-rooted trees and shrubs. Another parameter that governs the subsurface response is the threshold depth of water in the shallow aquifer for “revap” to occur (REVAPMN). Movement of water from the shallow aquifer to the root zone or to plants is allowed only if the depth of water in the shallow aquifer is equal to or greater than the minimum “revap.” A third parameter is the threshold depth of water in the shallow aquifer required for return flow to occur to the stream (GWQMN). Two other parameters that govern watershed response include the baseflow alpha factor and ground water delay. The baseflow alpha factor (ALPHA_BF), or recession constant, characterizes the ground water recession curve. This factor approaches zero for flat recessions and approaches one for steep recessions. The ground water delay (GW_DELAY) is the time required for water leaving the bottom of the root zone to reach the shallow aquifer. A sixth factor is the deep aquifer percolation fraction which governs the fraction of percolation from the root zone to the deep aquifer (RCHRG_DP).

Parameters that govern basin response in SWAT include channel hydraulic conductivity (CH_K2) and surface runoff lag time (SURLAG). CH_K2 controls the movement of water from the streambed to the subsurface for ephemeral or transient streams, and SURLAG provides a storage factor in the model that allows runoff to reach a subbasin outlet when the time of concentration is greater than one day.

Watershed Delineation and Model Calibration. For modeling purposes in SWAT, a watershed is partitioned into a number of subbasins. Each subbasin delineated within SWAT is simulated as a homogeneous area in terms of climatic conditions but with additional subdivisions within each subbasin to represent different soils and land use types. Each of these individual land use and soil areas is referred to as a hydrologic response unit (HRU). Table 1 lists the respective number of subbasins and HRUs that were delineated for each of the USAWs and subwatersheds within the LWREW. Delineated HRUs were assumed to be spatially uniform in terms of soils, land use, topography, and climate data. To avoid excessive computational time for model simulations, the number of HRUs in the delineation of subwatershed 526 was constrained by a threshold based on a land use and soil type covering an area of at least 5% and 20%, respectively, within any given subbasin.

A noticeable difference between the USAWs and the subwatersheds delineated in this study was the size of the respective subbasins. On average, the subbasin size of the USAWs was 0.015 km^2 (0.0058 mi^2) and that of the subwatersheds was 2.60 km^2 (1.004 mi^2). Model testing revealed that scaling up subbasin size from 0.015 to 2.60 km^2 (0.0058

Table 3
Parameter values calibrated in SWAT for the Little Washita River experimental subwatersheds.

SWAT parameter	Land cover type	Initial model input value	Calibrated values: Unit source area 5273	5234	5375	5269	Little Washita 483	442	526
CN2									
	Winter wheat	73	*	*	73	73	73	73	73
	Bermuda grass	58	58	*	*	*	*	*	58
	Pasture/range	61	*	59	*	*	61	61	61
	Mixed agricultural/misc.	77	*	*	*	*	*	77	77
	Alfalfa	59	*	*	*	*	*	59	59
	Forest	55	*	*	*	*	55	55	55
ESCO		0.95	0.76	0.03	0.92	0.96	0.49	0.76	0.76
SOL_AWC†		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GW_REVAP		0.02	*	*	*	*	0.022	0.02	0.02
REVAPMN		1.00	*	*	*	*	0	0.97	248
GWQMN		0.0	*	*	*	*	0	0	301
GW_DELAY		31	*	*	*	*	97	111	248
ALPHA_BF		0.05	*	*	*	*	0.97	1	0.228
RCHRG_DP		0.05	*	*	*	*	0	0.007	0.19
SURLAG		4.00	0.6	0.6	0.6	0.6	0.6	2.1	1.46
CH_K2		0.0	0	0	0	0	15	114	149

* = not applicable.
† = parameter value expressed as percent change from initial model input value.

to 1.004 mi²) did not affect surface runoff response of the model. It is recognized, however, that such a change in subbasin size does impact the simulation of sediment, nutrients, and other water quality variables in the model (Arabi et al. 2006). Since this study only addressed the runoff response of the model, further analyses of subbasin size were not implemented.

Two evaluation criteria were used to calibrate monthly runoff. The first evaluation criterion used was the percent bias (PBIAS), which is a measure of the average tendency of the simulated flows to be larger or smaller than their observed values. The optimal PBIAS value is 0; a positive value indicates a model bias toward underestimation, whereas a negative value indicates a bias toward overestimation (Gupta et al. 1999). PBIAS may be expressed as

$$PBIAS = \sum_{k=1,n}^{n} (Q_{k\ obs} - Q_{k\ sim})(100) / \sum_{k=1,n}^{n} (Q_{k\ obs}) \quad (1)$$

where PBIAS = deviation of runoff (%), $Q_{k\ obs}$ = observed monthly runoff (mm), and $Q_{k\ sim}$ = simulated monthly runoff (mm).

The second evaluation criterion was the model coefficient of efficiency (NSE) (Nash and Sutcliffe 1970), which Sevat and Dezetter (1991) found to be the best objective function for reflecting the overall fit of a hydrograph. NSE expresses the fraction of the measured runoff variance that is reproduced by the model:

$$NSE = 1 - \left[\left(\sum_{k=1,n}^{n} Q_{k\ obs} - Q_{k\ sim} \right)^2 / \sum_{k=1,n}^{n} (Q_{k\ obs} - Q_{mean})^2 \right] \quad (2)$$

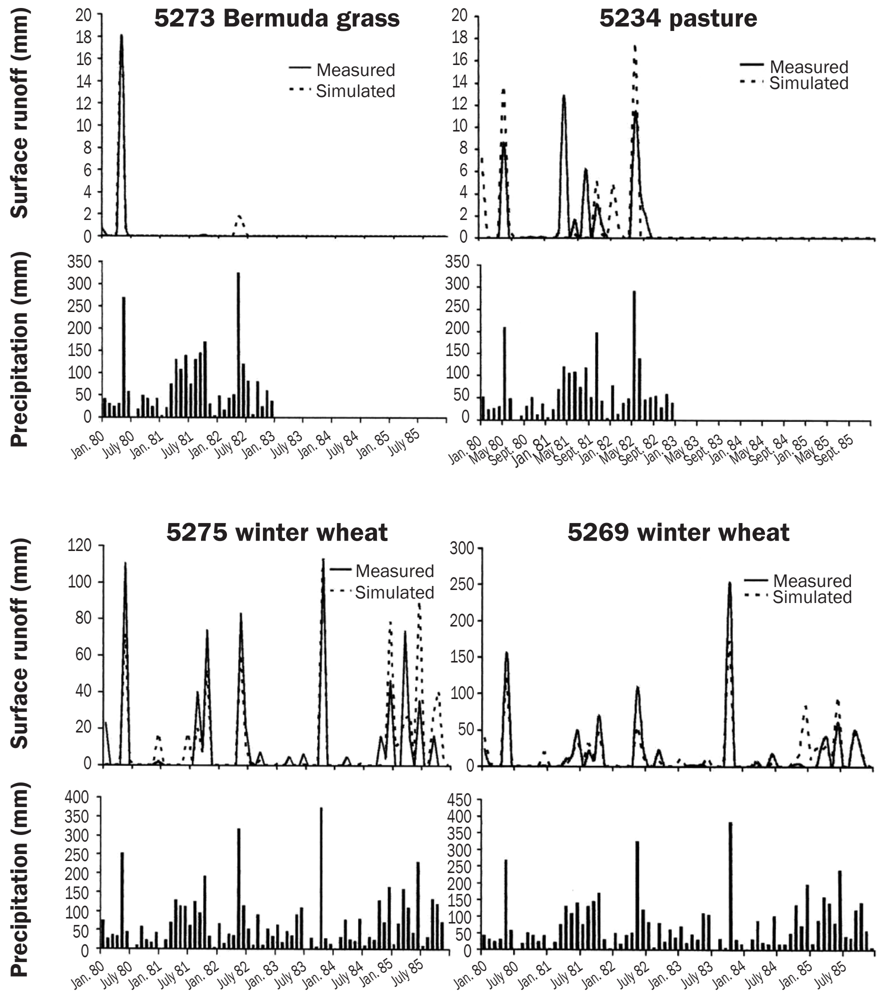
where NSE = Nash Sutcliffe coefficient of efficiency and Q_{mean} = mean observed monthly runoff during the evaluation period (mm).

The value of NSE in equation (2) may range from zero to one, with one representing a perfect fit of the data. Simulation results are considered to be good for NSE values greater than 0.75, while for values of NSE between 0.75 and 0.36, the simulation results are considered to be satisfactory (Motovilov et al. 1999). For this study NSE values less than 0.36 were considered to be unsatisfactory.

The following procedure was used to calibrate model parameters in SWAT that govern only the surface runoff response on the USAWs. The default value of the SOL_AWC was assumed to be valid for soil conditions on each of the USAWs. Field observations of the watershed were used to select appropriate values of the CN2 as published by the USDA SCS (1986). These CN2 values for the various land cover types are listed in table 3 and were not adjusted during calibration with the exception of the value for USAW 5234, which could only be achieved by a small, downward adjustment in the curve number and a value of ESCO near zero. The ESCO was then calibrated manually to achieve the highest possible monthly NSE for a PBIAS within ±3% so that measured versus simulated hydrographs compared well and mass balance was preserved. This method of manual calibration was implemented by a trial and error approach that initially involved changing the value of ESCO incrementally by 0.1 to sample the entire range from 0.0 to 1.0 for this parameter. Once an approximate value of ESCO was determined, the parameter was fine tuned by implementing incremental changes of 0.01 and comparing resultant values of NSE for each calibration trial. Since it was not necessary to calibrate parameters governing the subsurface response of the USAWs, the method described for calibrating the surface runoff response was a plausible approach to model calibration, due to the uncertainties associated with relating ESCO to soil and land management properties present on the respective USAWs.

A similar procedure described above for the calibration of the USAWs was used to calibrate subwatersheds 483, 442, and

Figure 2
Comparison of measured versus simulated surface runoff and precipitation for unit source watersheds 5273, 5234, 5275, and 5269.



526. The default value of SOL_AWC was assumed to be valid for soil conditions on each of the subwatersheds, and field observations were used to select appropriate values of the CN2. The remaining nine parameters in SWAT were calibrated in such a way to ensure that mass balance and the appropriate contributions of surface and subsurface flow to total flow were achieved. Following calibration, a baseflow separation technique developed by Arnold and Allen (1999) was used to estimate the relative proportions of surface and subsurface flow computed by the model for each of the subwatersheds.

Results and Discussion

A comparison of measured versus simulated average runoff, PBIAS, and NSE for each of the four LWREW USAWs and the three subwatersheds is presented in table 4. The shorter period reported in the table for USAWs 5273 and 5234 reflects the fact that this was the only period that runoff measurements were made from these drainages. Average annual simulated surface runoff from the Bermuda grass (5273) and pasture (5234) USAWs were 6.7 mm (0.26 in) and 17.1 mm (0.67 in), respectively, for the 1980 to 1982 period, which contrasts sharply with average annual simulated surface runoff of 88 mm (3.46 in) and 140 mm (5.51 in) for the winter wheat USAWs 5275 and 5269, respectively, for the same three year period. Results obtained from the calibration performed on the USAWs would suggest that the winter wheat land cover type produces about five to eight times as much surface runoff as does the pasture cover type. Based on monthly values of NSE, surface runoff response on two of the USAWs was considered good, one was considered satisfactory, and one was considered unsatisfactory.

Poor runoff performance on USAW 5234 was attributed to inaccuracies in representing the precipitation signal in SWAT since there were no precipitation gauges in the immediate vicinity of this catchment. A comparison of measured versus simulated surface runoff for USAW 5234 shows that SWAT overestimated runoff events occurring in January and May of 1980 and 1982, and missed events that occurred in March, April, and May of 1981 (figure 2). For the calibration achieved on USAWs 5275 and 5269, the model tended to underestimate surface runoff for events occurring between 1980 and 1984 when average annual precipitation was 780 mm (30.7 in) and 830 mm (32.7 in), respectively. SWAT tended to overestimate runoff during the wet period of 1985 on USAWs 5275 and 5269 when average annual precipitation for that year was 990 mm (39.0 in) and 1120 mm (44.1 in), respectively.

To substantiate assumed values of CN2 and SOL_AWC used for the USAWs, model simulations were performed on subwatershed 483 (4.3 km^2 [1.7 mi^2]) and subwatershed 442 (33.3 km^2 [12.9 mi^2]) of the LWREW. Although selected curve number values for these subwatersheds were similar to those used on the four USAWs, the value of the ESCO equal to 0.76 for subwatershed 442 could only be likened to the calibrated value of 0.76 on USAW 5273. Comparison of monthly measured versus simulated total runoff shows that the model performed much better on subwatersheds 442 and 526 than on 483 in that for the latter, SWAT underestimated runoff from the fall of 1996 to the summer of 1997 and overestimated runoff for nearly all of 1998 (figure 3). Although a number of possibilities for explaining discrepancies in model performance on subwatershed 483 were examined, the most plausible reason was the fact that the precipitation input signal for this watershed was based on inverse distance weighting of the four nearest rain gauges lying outside of the watershed boundary (Van Liew et al. 2003).

An additional computation that was made for subwatershed 483, 442, and 526 was to compare the fraction of surface runoff to total runoff for the respective measured versus simulated periods of record. The baseflow separation technique developed by Arnold

Table 4

Simulated period of record, measured versus simulated average annual runoff, percent bias, monthly coefficient of efficiency, and fraction of surface runoff to total runoff for the Little Washita River experimental subwatersheds.

Subwatershed	Area (km^2)	Time series	Measured runoff (mm)	Simulated runoff (mm)	Percent bias	Monthly NSE	Measured fraction of surface runoff	Simulated fraction of surface runoff
5273	0.0147	1980 to 1982	6.6	6.7	–3.0%	0.98		
5234	0.0116	1980 to 1982	17.1	17.1	0.1%	–0.04		
5275	0.0060	1980 to 1985	117	118	–0.9%	0.69		
5269	0.0417	1980 to 1985	169	168	0.6%	0.93		
483	4.3	1996 to 2000	118	118	–0.2%	0.38	0.29	0.30
442	33.3	1993 to 1999	166	166	–0.5%	0.72	0.19	0.22
526	160	1979 to 1985	121	121	0.9%	0.90	0.48	0.49

Note: NSE = Nash Sutcliffe coefficient of efficiency.

and Allen (1999) was used to filter the measured runoff data and simulated output from the model into surface and subsurface components. Results of this analysis showed that the measured versus simulated fraction of surface runoff to total runoff was 0.29 and 0.30 for subwatershed 483, 0.19, and 0.22 for subwatershed 442, and 0.48 and 0.49 for subwatershed 526 the respective time series (table 4). Table 5 provides a breakdown of the respective amounts of surface and total runoff simulated by land cover type for subwatershed 526. Relative differences in the respective proportions of surface to total runoff are apparent from the table and are indicative of differences in the curve number. For example, the surface runoff to total runoff fraction is 37/110 mm (1.5/4.3 in) or 0.34 for pasture/range (CN2 = 61) and 100/136 mm (3.9/5.4 in) or 0.74 for winter wheat (CN = 73). The higher surface runoff to total runoff fraction for winter wheat reflects in part the impact of summer fallow conditions on annual runoff rates. Results obtained in this study for LWREW subwatershed 526 would suggest that for the selected calibration period, winter wheat produces about 2.7 and 1.2 times as much surface runoff and total runoff, respectively, as does pasture/range. A simulated winter wheat to pasture/range total runoff ratio of about 1.2 compares favorably to a measured ratio of about 1.3 for similar soil and land cover conditions in a long term study conducted on USAWs adjacent to the LWREW (Water Quality and Watershed Research Laboratory 1983). However, the difference in this study between the proportion of surface runoff produced from winter wheat compared to pasture/range for the USAWs (5 to 8 times) versus subwatershed 526 (2.7 times) illustrates one of the disparities in

Figure 3

Comparison of measured versus simulated total runoff and precipitation for subwatersheds 483, 442, and 526.

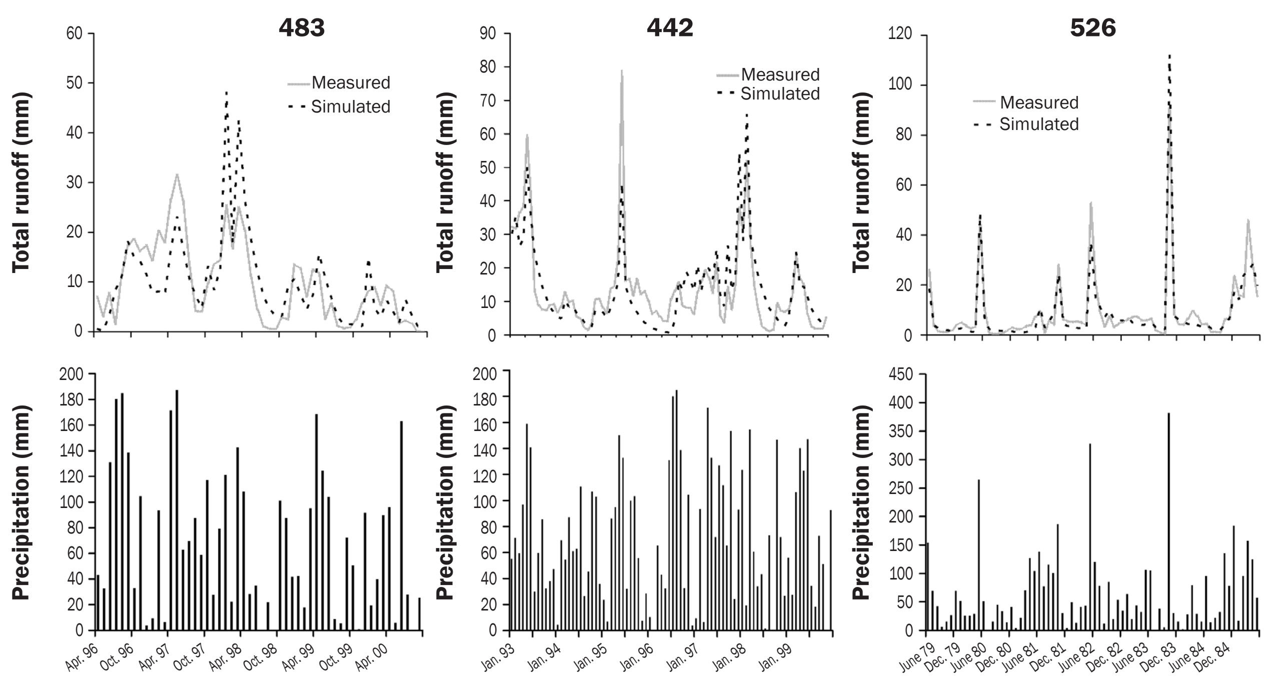


Table 5
SWAT simulated runoff by land cover for subwatershed 526.

Land cover	Percentage of basin	Surface runoff (mm)	Total runoff (mm)
Pasture/range	61%	37	110
Alfalfa	1%	30	105
Forest	8%	21	88
Agricultural–misc.	9%	153	191
Winter wheat	21%	100	136

utilizing USAW runoff data for calibration of a watershed scale model such as SWAT.

As described earlier, the calibration procedure used for estimating the surface runoff response on the USAWs consisted of adjusting values of ESCO with the assumption that default values of SOL_AWC were valid and published values of CN2 were applicable for known field conditions on the LWREW. Based on this assumption, it is apparent that a distinct contrast exists between calibrated values of ESCO for Bermuda grass and pasture versus winter wheat. The difference between the ESCO value of 0.76 for USAW 5273 (Bermuda grass) and 0.03 for USAW 5234 (pasture) may be explained in part by the difference in land management but more importantly by the difference in soil type: the former is a silt loam while the latter is a loam. However, differences between USAW 5273 and the winter wheat USAWs 5275 and 5269 cannot be easily reconciled, since a comparison of soils, topographic, and vegetative properties among these three USAWs reveals that land cover and management are the only apparent differences. To illustrate the importance of this parameter on simulations performed by SWAT, a simple set of tests was conducted on USAWs 5273 and 5275. The sensitivity of ESCO on surface runoff was evaluated by changing the calibrated value of 0.76 to 0.92 on USAW 5273. This change in ESCO resulted in a corresponding increase in surface runoff of 32%. Similarly, a decrease in ESCO from 0.92 to 0.76 for UWAW 5275 led to a decrease in runoff of 54%. These tests demonstrate the sensitive nature of this parameter in governing surface runoff in the model, and largely reflect variations in the evaporative demand throughout the soil zone due to differences in crop water requirements and the impact of crop residue as a result of tillage operations.

Model simulations to evaluate the impact of varying ESCO by land cover on LWREW 526 revealed that if a value of 0.92 was selected for winter wheat and 0.76 for all other land use types on the watershed, the resulting calibration would lead to a surface runoff to total runoff fraction that was more than 15% too high. As noted by Neitsch et al. (2002), differences in re-evaporation of moisture based on crop or plant type are accounted for in the "revap" (GW_REVAP) calibration parameter in SWAT that governs the movement of subsurface flow into overlying unsaturated layers. In adherence to the distinction between ESCO which controls surface runoff response and GW_REVAP that controls subsurface flow, results of this study would suggest that the magnitude of the ESCO is largely dependent upon soil properties and land management practices present on the landscape rather than crop type.

Results of this study do not provide sufficient information to adequately evaluate the effect of scaling up parameter values of the ESCO from a unit source area to a watershed scale. This is because differences that exist among calibrated values of ESCO from the four USAWs reflect a degree of uncertainty that makes extension of this parameter difficult on larger watersheds such as LWREW 526. Findings of this study therefore suggest that USAW data may best be used for the parameterization of the CN2 in the model. To better understand the role of ESCO, CN2, and SOL_AWC on surface runoff in SWAT, a wider range of USAW data is needed to relate land management and soil properties to processes such as infiltration, soil moisture changes, and soil evaporation. Although not measured in this study, observations of soil evaporation for specific soil and management conditions could be especially helpful in estimating values of ESCO in the model. Alternatively, subdaily time step computations with the Green and Ampt (Green and Ampt 1911) infiltration method in SWAT or other simulation models that are more physically based than SWAT may provide the necessary insights in relating particular land management and soil conditions that characterize USAWs to parameters that govern runoff response at the watershed scale.

Summary and Conclusions

The purpose of this investigation was to determine whether or not model parameters that govern the surface runoff response in SWAT that were calibrated from USAWs could be scaled up to provide accurate runoff simulations at a watershed scale. Model testing was conducted on four USAWs that consisted of homogeneous improved Bermuda grass, poor native grass pasture, and conventional tilled winter wheat land cover types, and three larger subwatersheds of the LWREW in southwestern Oklahoma. Data from the USAWs were used to calibrate parameters in SWAT that govern the surface runoff response of the model. Model simulations performed on the 4.5 km^2 (1.7 mi^2) subwatershed 483 and 33.3 km^2 (12.9 mi^2) subwatershed 442 were used to substantiate model calibrations with the USAWs. The strengths and weaknesses associated with extending values of these calibrated parameters to the larger, 160 km^2 (61.9 mi^2) subwatershed 526 were then evaluated by examining both the surface and total components of runoff generated by the model.

Test results from model simulations performed in this study on USAWs demonstrate that calibrated values of the soil evaporation compensation factor referred to as ESCO may vary over a wide range from nearly zero to one. Simulation results indicate that if a value of ESCO that was calibrated from the USAW data for winter wheat was applied at the watershed scale, it would lead to model simulations that give unrealistically high values of surface runoff. Findings from this study suggest that the ESCO reflects not only soil field conditions for which it was intended to describe but also the impact of land management practices on surface runoff response.

This investigation accentuates some of the difficulties associated with relating point or USAW measurements to watershed scale applications. Due to uncertainties in relating the ESCO to soil and land management properties, results of this study suggest that runoff data from USAWs may be best suited for calibrating infiltration functions or verifying values of the CN2 for watershed simulations. Findings of this research point to the need to develop new or improved algorithms that relate infiltration processes and changes in soil moisture to soil cracking and crusting. Simulation models such as the DWSM (Borah and Bera 2003) or the KINEROS (Smith et al. 1995) that are more physically based than SWAT may also provide valuable insights in relating land cover conditions that characterize USAWs to parameters that govern runoff response at the watershed scale.

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